

Pacific Island Developing Country Water Resources and Climate Change

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As one commentator has observed, “[O]ne ironic and tragic aspect of this environmental crisis of greenhouse emissions is the fact that those parts of the world least responsible for creating the global warming problem will be the first to suffer its horrifying consequences” (Panjabi 1993, Burns 2000). Pacific Island Developing Countries (PIDCs) are responsible for only 0.03 percent of the world’s carbon dioxide emissions, and the average island resident produces only one-quarter of the emissions of the average person worldwide (Hay 1999). Yet it is anticipated that these nations will experience some of the earliest and most severe consequences of climate change over the next two centuries (IPCC 2001a, Burns 2001). While the popular press has focused on the threat of inundation of island coastal areas by rising sea levels, perhaps the most critical near- and long-term threat to these nations is the possible impacts of climate change on freshwater quality and availability (Meehl 1996, East-West Center 2001). This chapter focuses on the potential impacts of climate change on the already severely strained freshwater resources of PIDCs.

PIDCs and Freshwater Resources

There are nearly 30,000 islands in the Pacific Ocean, 1,000 of which are populated (UNEP 1998) (see Figure 5.1). Polynesian peoples populated Tonga, the Cook Islands, and French Polynesia during the present interglacial period (Wilkinson 1996). Melanesian peoples began to colonize the high islands of the western Pacific (Papua New Guinea, Solomon Islands, Vanuatu, and New Caledonia) as far back as 40,000 years ago (Tutangata 1996), millennia before settlement began in Europe (Tutangata 1996), and Micronesian peoples settled on many low islands, such as Micronesia and the Marshall Islands, in the last 2,000 years (Wilkinson 1996).

PIDCs consist of 22 political entities, 15 of which are politically independent (Campbell 1996), spread out over 28 million square kilometers of ocean (Tutangata



FIGURE 5.1 Pacific Island Developing Countries.

2000) (see Table 5.1). Almost all PIDCs lie between 30° north and 30° south latitude, between the Tropic of Cancer and the Tropic of Capricorn in the southwestern portion of the Pacific (U.S. Naval Meteorology and Oceanography Command 2001). With the exception of Papua New Guinea and Fiji, all PIDCs fall within the United Nations' definition of "small island states," which are islands with land areas smaller than 10,000 square kilometers and with fewer than 500,000 inhabitants (Pernetta 1992, Bequette 1994). The majority of countries in the region fall well below these thresholds, with populations below 200,000 and land areas well below 1,000 square kilometers, and many fall into the category of "very small islands," with land areas less than 100 square kilometers or a maximum width of 3 kilometers (Dijon 1994). The combined population of PIDCs in the region is slightly over 6 million, the lion's share being in Papua New Guinea (Kaluwin and Smith 1997). PIDCs comprise only 10 percent of the land area in the Pacific (Asian Development Bank 2001).

Pacific islands are traditionally classified as "high" or "low," with a further subdivision into continental and volcanic islands in the former category and atolls and raised limestone islands on the other (Campbell 1996). In most cases, PIDCs are a combination of these island types (see Table 5.2). High islands primarily consist of rugged volcanic mountains surrounded by fringing or barrier reefs. They may also have a fringe of low-lying coastal plains surrounding the mountainous interior. Atolls consist of limestone reef deposits laid down on an underlying volcanic cone. In most cases, the portion of atolls above sea level is usually not more than a few square kilometers

TABLE 5.1 Profile of Pacific Island Developing Countries

Country	Political Status	Population (2000 Est.)	Land Area (Sq. Km.)
America Samoa	Territory of the United States	65,446	199
Commonwealth of the Northern Marianas	Commonwealth in political union with the United States	71,912	477
Cook Islands	Self-governing, in free association with New Zealand	20,407	240
Federated States of Micronesia	Independent Nation	133,144	702
Fiji	Independent Nation	832,494	18,270
French Polynesia	Overseas territory of France	249,110	4,167
Guam	Territory of the United States	154,623	541.3
Kiribati	Independent Nation	91,985	717
Nauru	Independent Nation	11,845	21
New Caledonia	Overseas territory of France	201,816	19,060
Niue	Self-governing, in free association with New Zealand	2,113	260
Palau	Independent Nation	18,766	458
Papua New Guinea	Independent Nation	4,926,984	462,840
Pitcairn Islands	Overseas territory of the United Kingdom	54	47
Republic of the Marshall Islands	Independent Nation	68,126	181.3
Samoa	Independent Nation	179,466	2,860
Solomon Islands	Independent Nation	466,194	28,450
Tokelau	Territory of New Zealand	1,458	10
Tonga	Independent Nation	102,321	748
Tuvalu	Independent Nation	10,838	26
Vanuatu	Independent Nation	189,618	14,760
Wallis and Futuna	Overseas territory of France	15,283	274

Source: All data derived from: U.S. Central Intelligence Agency, *The World Factbook 2000*, <http://www.odci.gov/cia/publications/factbook/>, site visited on Sept. 20, 2001.

(Granger 1996). Raised atolls are uplifted coral atolls that consist almost entirely of limestone and dolomite, some rising 60–70 meters above sea level (Solomon and Forbes 1999, Granger 1996).

Description and Status of Freshwater Resources

The freshwater resources of small island states can be classified as either “conventional” or “nonconventional.” Conventional resources include rainwater collected from artificial or natural surfaces, groundwater, and surface water. Nonconventional resources include seawater or brackish groundwater desalination, water importation by barge or submarine pipeline, treated wastewater, and substitution (such as the use of coconuts during droughts) (Falkland 1999a).

Rainwater. Rainwater collections systems, such as rainwater catchments on the roofs of individual houses or paved runways, are commonly used on many PIDCs. On some very small low-lying PIDCs, such as Tuvalu, the northern atolls of the Cook Islands, and some of the raised coral islands of Tonga, rainwater collection on roofs or

TABLE 5.2 Terrain of Pacific Island Developing Countries

Country	Terrain
America Samoa	5 volcanic islands and 2 coral atolls
Commonwealth of the Northern Marianas	Limestone (southern islands); volcanic (northern islands)
Cook Islands	Coral atolls (north); volcanic (south)
Federated States of Micronesia	High volcanic islands; low coral atolls
Fiji	Primarily mountains of volcanic origins
French Polynesia	Rugged high islands and low atolls
Guam	Volcanic origin, limestone plateau
Kiribati	Primarily low-lying atolls
Nauru	Raised atolls
New Caledonia	Coastal plains with interior mountains
Niue	Raised atolls
Palau	High mountainous islands to low coral islands
Papua New Guinea	Primarily mountainous with coastal lowlands
Pitcairn Islands	Rugged volcanic formation
Republic of the Marshall Islands	Raised atolls
Samoa	Narrow coastal plain with volcanic, rocky, rugged mountains in interior
Solomon Islands	Primarily rugged mountains with low coral atolls
Tokelau	Low-lying coral atolls enclosing large lagoons
Tonga	Limestone bases with uplifted coral formation; limestone overlying volcanic bases
Tuvalu	Very low-lying and narrow coral atolls
Vanuatu	Primarily mountains of volcanic origin
Wallis and Futuna	Volcanic origin, low hills

Source: All data derived from: U.S. Central Intelligence Agency, *The World Factbook 2000*, <http://www.odci.gov/cia/publications/factbook/>, National Communications, Non-Annex I parties, United Nations Framework Convention on Climate Change, <http://www.unfccc.de/resource/natc>, sites visited on Sept. 18, 2001.

community buildings is the sole source of fresh water. On other islands in the region, rainwater is a supplementary source of water that is used for more essential needs, such as cooking and drinking (Falkland 1999b).

Groundwater. Groundwater occurs on small island states in two main types of natural reservoirs (aquifers), perched and basal. Perched aquifers occur where an impermeable layer exists in the zone of aeration,¹ creating a groundwater formation above the water table, or when groundwater is retained in compartments by a series of vertical volcanic dikes (Falkland and Custodio 1991). They are similar to the aquifers found on large islands or continents. Basal aquifers may occur on either high or low islands in the form of coastal aquifers or rainwater that percolates through an island

1. The zone of aeration is "a subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillarity; and containing air or gases generally at atmospheric pressure. [I]t extends from the ground surface to the water table." Society of Professional Well Log Analysts, Glossary of Water Terms, <http://www.spwla.org/gloss/reference/glossary/glossz/glossz.htm>, site visited on September 25, 2001.

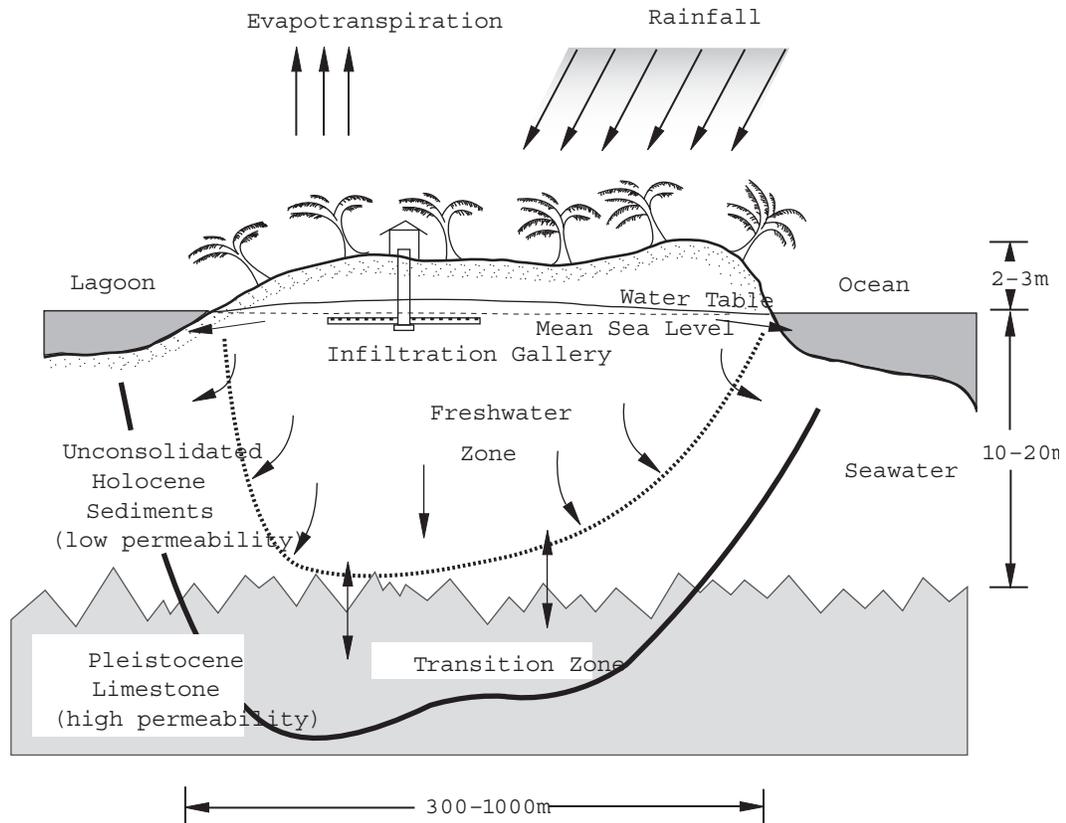


FIGURE 5.2 Cross-section through a small coral island showing main features of a freshwater lens (exaggerated vertical scale).

Source: Falkland 1999

and floats on the denser salt or brackish water in what is termed a Ghyben-Herzberg lens (Whittaker 1998) (see Figure 5.2).²

The volume of freshwater lenses is roughly proportional to the width and surface area of an island and is also influenced by factors such as rainfall levels, the permeability of the rock beneath islands, and salt mixing due to storm- or tide-induced pressure (Roy and Connell 1991). While such lenses may be as thick as 20 meters on some islands, on raised coral atolls, such as Nauru and many of the islands of Tonga, they may be no more than 10–20 centimeters thick (Falkland and Custodio 1991).

Most PIDCs rely on groundwater resources for at least some of their water needs, and it is the primary source on several of these islands, including Kiribati (UNESCO 2001). Many low-lying atoll islands supplement rainwater supplies with storage capacity in the freshwater lens (Small Island Developing States Net 2001).

Surface water. Surface water, in the form of ephemeral and perennial streams, springs, lakes, and swamps, is found mainly on high islands in PIDCs (Falkland 1999a). Surface water is rarely found on low islands such as coral atolls and limestone islands

2. The Ghyben-Herzberg principle provides that “freshwater recharge to an island will tend, when restrained and protected from wave and tidal mixing by the porous medium, to form a lens of freshwater which floats upon the underlying seawater in the formation.” M.E. Herman, R.W. Buddemeier, and S.W. Wheatcraft, “A layered aquifer model of atoll island hydrology: Validation of a computer simulation,” *J. Hydrology*, vol. 84, 1986, pp. 303, 304.

because of the high infiltration capacity of the soils and rocks found on such islands (Falkland and Custodio 1991). In those rare cases where surface water is found on low islands, it is likely to be in the form of shallow, often brackish lakes (UNEP 1998).

On some high islands in the Pacific, surface water is the predominant source of fresh water because gravity-fed water systems are more cost-effective than developing and pumping from groundwater sources (Falkland and Custodio 1991). For example, surface water provides more than 95 percent of the water requirements in French Polynesia (Falkland and Custodio 1991). Surface water also contributes to the freshwater supply in Nauru, Palau, and on the high islands of the Cook Islands (Falkland and Custodio 1991).

Nonconventional sources. Given the costs or nonfeasibility of nonconventional alternatives for many PIDCs, especially small coral islands, most fresh water on PIDCs is derived from conventional sources (UNEP 1998). However, approximately 60 percent of the water requirements on the island of Nauru are produced from desalination (Ghasemmi 1997), and some other islands have established desalination plants for specific uses, such as tourist resorts (Falkland 1999a).

Nauru received most of its water in ships until it installed a desalination plant (see Chapter 2), and some of the small islands of Fiji and Tonga also receive water from nearby islands by barge or boat (Falkland 1999a). During severe droughts or natural disasters some of the small islands of Fiji, Kiribati, and the Marshall Islands have relied on coconuts for water (Falkland 1999a). Finally, nonpotable sources, including sea water, brackish groundwater and wastewater, are used for toilet flushing and fire fighting on a number of PIDCs, including Kiribati and the Marshall Islands (Falkland 1999a).

Threats to Freshwater Resources

Fresh water is an imperiled and extremely limited resource on most PIDCs. As the United Nations Economic and Social Commission for Asia and the Pacific recently concluded, “Freshwater is an essential, and threatened, resource. Throughout the Pacific, smaller islands, and the leeward side of large high islands, experience difficult, and sometimes life threatening, deficiencies of unpolluted water supplies” (Ministerial Conference 2001).

A recent survey by the Asian Development Bank (ADB) found that only 50–75 percent of the residents of Samoa and only 44 percent of the residents in Kiribati had access to safe water (Hoegh-Guldberg et al. 2000). In Papua New Guinea, only 10 percent of the rural population has access to safe drinking water (Lauerma 1997).

Rapid population increases in PIDCs, largely attributable to advances in health care, are placing increasing strain on the limited water resources of many PIDCs (Falkland and Custodio 1991). Over-pumping from fragile groundwater resources to meet increasing water needs can lead to saltwater intrusion and the ultimate loss of supply (South Pacific Applied Geoscience Commission 2001a). These pressures will be exacerbated in the future. Population in the region may double in the next quarter century, compared to an estimated global population doubling over the next 50 years or so (East-West Center 2001, Larson 2000). Water supplies are also threatened by aging and poorly installed infrastructure that results in water leaks of up to 70 percent from the reticulation system (South Pacific Applied Geoscience Commission 2001b).

Water shortages on PIDCs are also exacerbated by other natural and anthropogenic factors. Rapid urbanization in many PIDCs has resulted in a substantial increase of pollutants over the past few decades, including nutrients, biochemical oxygen

demand, solids, and microbial pollution (UNEP 2000). Moreover, many PIDCs have inadequate sewage disposal infrastructure (Brodie, Prasad, and Morrison 2001). This has resulted in the contamination of many water systems, producing high levels of diarrheal and other infectious diseases (Falkland 1999b). The groundwater resources of small coral islands are particularly threatened by pollution because these islands are characterized by thin, highly permeable soil zones (Falkland and Custodio 1991).

Many PIDCs rely on a single source of water, rendering them extremely vulnerable to natural variability in precipitation patterns or changes in storm tracks. This is particularly true for the atoll states in the region (Salinger et al. 1995). El Niño/Southern Oscillation (ENSO) episodes in the past two decades have reduced precipitation by as much as 87 percent in the western Pacific while resulting in unusually high rainfall in the central Pacific. ENSO is the most important mode of the Earth's seasonal and year-to-year climate variability. El Niño, the warm phase of ENSO, refers to climate conditions in the tropical Pacific characterized by unusually warm sea-surface temperatures and weak trade winds. La Niña refers to the climate state characterized by anomalously cool sea-surface temperatures and stronger than average trade winds (CIG 2001; Kripalani, Kulkarni, and Sabade 2001).

Drought associated with ENSO events have depleted rainfall collection supplies and the freshwater lenses and perched aquifers on many PIDCs. For example, in 1998, 40 atolls of Micronesia ran out of water during an ENSO event (Tutangata 1996), resulting in the declaration of a national emergency. In the same year, rainwater tanks in substantial parts of Kiribati dried up and shallow groundwater reserves became brackish (World Bank 2000). The main island of the Marshall Islands also had access to drinking water for only seven hours every fourteen days, and rationing occurred on all islands in the North Pacific (East-West Center 2001). Tropical storms may also imperil water supplies. Ocean waves may overtop small low-lying islands, contaminating freshwater lenses with saltwater for months and damaging rainfall collection systems (Falkland and Custodio 1991, Falkland 1999b). As I will outline in the next section of this chapter, the water problems of PIDCs are likely to be severely increased by projected human-induced climate change over the next century and beyond.

Climate Change and PIDC Freshwater Resources

A Science Overview

The surface of the earth is heated by solar radiation emanating from the sun at short wavelengths between 0.15 and 5 μm . Each square meter of the earth receives an average of 342 watts of solar radiation throughout the year (IPCC 2001b). Approximately one-third of the incoming solar radiation is reflected back to space in the form of thermal infrared, or longer-wave radiation, at wavelengths of 3–50 μm (IPCC 1994). Of the remainder, a portion is partly absorbed by the atmosphere, but most (168 watts per square meter) is absorbed by land, ocean, and ice surfaces (IPCC 2001b).

Some of the outgoing infrared radiation is absorbed by naturally occurring atmospheric gases—principally water vapor (H_2O)—as well as carbon dioxide (CO_2), ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and clouds (Benarde 1992). This absorption is termed the *natural greenhouse effect* because these gases, which are termed *greenhouse gases*, operate much like a greenhouse: they are “transparent” to incoming short-

wave radiation, but “opaque” to outgoing infrared radiation, trapping a substantial portion of such radiation and re-radiating much of this energy back to the earth's surface (University of Capetown 1999). This natural process is critical to the sustenance of life on earth, elevating surface temperatures by about 33° Celsius (C) (University of Capetown 1999).

In the past, the net incoming solar radiation at the top of the atmosphere was balanced by net outgoing infrared radiation, contributing to climatic stability. For the past 8,000 years, the world's climate has been very stable, varying only within a range of + or – 1 degree C (Anonymous 1995). However, with the advent of fossil-fuel burning plants to support industry, mass use of automobiles, and the energy demands of modern consumers, “humans began to interfere seriously in the composition of the atmosphere” (Pearce 1995).

The burning of fossil fuels, mainly coal, oil and gas, has soared since the beginning of the Industrial Revolution. We now produce approximately 5.5 gigatons of carbon annually, nearly all of which enters the atmosphere as CO₂. An additional 1.5 gigatons is released into the atmosphere from land-use changes, such as deforestation. Cement production contributes a small additional amount (Hadley Centre 1999a). As a consequence, concentrations of carbon dioxide in the atmosphere have increased approximately 25 percent since 1850, from 270 to 280 parts per million (ppm) by volume in pre-industrial times to over 370 ppm today (Jardine 1994, IPCC 2001c),³ most of the increase occurring in the past fifty years (Wigley 2001). These concentrations have not been exceeded in the past 420,000 years, and the increase this century is “unprecedented” in the last 20,000 years (IPCC 2001d). Anthropogenic activities have also resulted in substantially increased atmospheric concentrations of other greenhouse gases, including methane (up 145 percent since 1750) and nitrous oxides (up 15 percent since 1750) (Warbrick and McGoldrick 1998), as well as new sources, such as chlorofluorocarbons and halons (Brasseur 1994). Tropical land use changes from the clearing of natural vegetation and secondary forests adds approximately another 2.4 gigatons annually to the atmosphere, representing 29 percent of the combined total of anthropogenic emissions (Fearnside 2001).

Increases in the concentration of greenhouse gases reduce the efficiency with which the earth's surface radiates to space. It results in an increased absorption of the outgoing infrared radiation by the atmosphere, with this radiation re-emitted at higher altitudes and lower temperatures (IPCC 2001d). This resulting change in net radiative energy, which is termed *radiative forcing*, tends to warm the lower atmosphere and the earth's surface (Wigley 2001). The amount of radiative forcing that occurs is dependent on the magnitude of increases in the concentrations of greenhouse gases, the radiative properties of the gases, and the concentrations of existing greenhouse gases in the atmosphere. Overall, CO₂ accounts for 65 percent of the total radiative forcing resulting from anthropogenically released greenhouse gases, methane contributes an additional 19 percent, chlorofluorocarbons, 10 percent, and nitrous oxide about 6 percent (Aplin 1999).

The latest assessment by the Intergovernmental Panel on Climate Change (IPCC)⁴ concluded that rising concentrations of greenhouse gases are the primary cause (IPCC

3. Parts per million is the ratio of the number of molecules of a gas (in this case carbon dioxide) to the total number of molecules of dry air.

4. The IPCC, comprised of 2,500 climate scientists from throughout the world, was established by the United Nations in 1988 to gather information and coordinate research related to climate change, to evaluate

2001c) for the increase in average global temperatures of about 0.6° C in the past century (United Kingdom Department 1999). “20th Century global mean temperature is at least as warm as any other century since at least 1400 AD,” notes the IPCC (1995). In the Northern Hemisphere, “the increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years” (IPCC 2001c). Warming has accelerated in the last 25 years, more than doubling that of the twentieth-century average (Stevens 1999).

In the South Pacific, surface air temperatures have increased by 0.3–0.8° C during the twentieth century, with the greatest increase in the zone southwest of the Southern Pacific Convergence Zone (IPCC 2001a). Temperature increases in this region are well in excess of global rates over the past century (IPCC 2001a).

Unfortunately, as we indicate in the next section, the unprecedented increases in temperatures over the last century are likely to be ratcheted up dramatically in this century, including in PIDCs.

Projections for the Twenty-first Century

Global projections. Predicting future climate is an extremely imposing task because it requires an assessment of the future state of a wide array of complex climatic components, including the atmosphere, the ocean, the cryosphere, land surfaces, the stratosphere, and the sun, as well as the interactions among these components (Wigley 2001). The only practical method to make such projections is through the use of mathematical models, derived from weather forecasting, to represent the earth’s energy and water cycles (Burns 2001a).

The most sophisticated of these models, general circulation models (GCMs), use a three-dimensional grid overlaying the surface of the earth with grid points 300–500 kilometers per side, within which cells are stacked about 20 layers deep (Hadley Centre 1999). Coupled atmosphere-ocean general circulation models seek to integrate atmosphere and ocean GCMs with sea-ice models and those of land-surface processes in an effort to obtain a realistic simulation of the earth’s climatic system, including feedbacks among these components (Hadley Centre 1999, Heilman 1999).

The vertical layers of a GCM represent levels in the atmosphere and depths in the ocean, dividing the surface of the planet into a series of horizontal boxes separated by lines similar to latitudes and longitudes (Hennessy 2001). Within each grid point, a series of equations are run on a supercomputer, producing simulations of key climatic components, including wind, air pressure, temperature, humidity, ice coverage, and land-surface processes (Barron 1995).

Climate models are usually run for several simulated decades, with the derived results compared to actual statistics on climatic conditions over this period, such as mean temperatures and precipitation. The models are then run with changes in external forcing, such as projected increases in atmospheric greenhouse gas concentrations, over a series of decades or centuries. The differences between these two “climates” provide an estimate of the consequent climate change (Schlesinger 1993).

In its *Third Assessment Report* on climate change, the IPCC concluded that by 2100 carbon dioxide concentrations will have risen 90–250 percent above pre-industrial

proposals for reducing greenhouse gas emissions, and to assess the viability of response mechanisms. Their most recent of three reports was released in mid-2001.

levels, to between 540 and 970 parts per million (IPCC 2001c). This will result in an increase of global average temperatures of 1.4 to 5.8° C by the end of this century, “very likely to be without precedent during at least the last 10,000 years” (IPCC 2001c). In a subsequent study, Wigley and Raper (2001) sought to assess the IPCC’s projected temperature range in probabilistic terms, concluding that the likeliest increase, with a 50 percent probability, will lie between 2.4–3.8° C, with further warming through the twenty-second century “virtually certain.”

The IPCC assessment also concluded that global mean sea level would rise by 9 to 88 centimeters by 2100 (with a mid-range estimate of approximate 50 centimeters) due to thermal expansion and the loss of mass from glaciers and ice caps (Wigley and Raper 2001). This is equivalent to a 200–500 percent acceleration over sea-level rise in the twentieth century (Nicholls and Mimura 1998).

The United Kingdom’s Hadley Centre’s most recent assessment on climate change concluded that temperatures could rise by 3° C and sea levels by 50 centimeters by 2100 if projected increases in greenhouse gas emissions are not reduced (Hadley Centre 1999).

Climate change in PIDCs. It must be emphasized that general circulation models remain a crude instrument for assessing regional climate trends because their resolution is often too coarse at this level:

[General circulation models] have difficulty in reproducing regional climate patterns, and large discrepancies are found among models. In many regions of the world, the distribution of significant surface variables, such as temperature and rainfall, are often influenced by the local effects of topography and other thermal contrasts, and the coarse spatial resolution of the GCMs can not resolve these effects. (Solman and Nunez 1999, Burns 2001b)

Resolution problems with GCMs are particularly acute for small landmasses in oceanic regions (SPREP 1999). In the case of PIDCs, many of the circulation features that dominate the climate of the islands in the region are inadequately simulated by the current generation of GCMs (SPREP 1999).

However, modeling of regional climate conditions has improved substantially in the past few years. In its most recent assessment of climate change impacts on small island states, the IPCC conducted a model validation exercise to assess the ability of leading GCMs to simulate present-day climate in the four major regions where the majority of small islands are located, including the Pacific. It concluded that several models “have reasonable capability in simulating the broad features of present-day climate and its variability over these regions” (IPCC 2001a). Moreover, Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO) has recently “nested” a higher resolution regional climate model within a GCM. The nested model is able to broadly simulate climatic conditions in the Pacific, although it diverges substantially from observed patterns of rainfall (Kondratyev and Cracknell 1998).

With the caveat that regional climate assessments remain speculative, the following section summarizes current projections of climate change in PIDCs by the IPCC and CSIRO.

The twenty-first century. The IPCC in its *Third Assessment Report* projects that temperatures in the Pacific will rise by approximately 2.0° C by 2050 and 3.0° C by 2080

(IPCC 2001a). While it is anticipated that temperatures in the region will rise less than global mean averages over the next century (IPCC 2001a), this range of change will constitute a dramatic increase over the substantial rise witnessed in the twentieth century. CSIRO's projections are consistent with this assessment, though its analysis reveals differential temperature increases in the region, with the greatest increases in north Polynesia (0.7–0.9° C) and the least warming in south Polynesia (0.7° C) (SPREP 1999).

The IPCC's *Third Assessment* projects that sea levels may rise in the region by as much as 5 millimeters per year over the next century (IPCC 2001a) and continue to rise in the twenty-second century due to lags in the climate effect (Klein and Nichols 1999). Moreover, sea-level rise will raise the baseline for storm surges (Hay and Kaluwin 1993), significantly increasing the vulnerability of coastal areas to inundation (Leatherman 1997). "Sea-level rise and storm surge effects are linearly additive; in other words, whatever storm surge occurs at a particular location under the current climate can simply be added to the sea-level rise at that location" (Hay and Kaluwin 1993, South Pacific Regional Environmental Programme 1999).

Several GCMs also predict more frequent ENSO-like patterns (IPCC 2001a). This could result in a 26–200 percent increase in rainfall over the central and east-central Pacific, with possible decreases in the Melanesian and Polynesian regions (IPCC 2001a, Jones 2000). Additionally, warming could also lead to increased extreme rainfall intensity and frequency. One model projects a doubling of the frequency of 100 millimeter per day rainfall events and a 15–18 percent increase in rainfall intensity over large areas of the Pacific (IPCC 2001a).

Projected buildups in greenhouse gas emissions will likely raise ocean temperatures and ocean surface water temperatures to above 26° C in the next century (NASA 2001; Karl, Nicholls, and Gregory 2001). This could result in a greater exchange of energy and add momentum to the vertical exchange processes critical to the development of tropical typhoons and cyclones. Some researchers estimate, therefore, that the occurrence of tropical typhoons and cyclones could increase by as much as 50–60 percent (NASA 2001, Schlesinger 1993, Haarsman 1993), and their intensity by 10–20 percent (IPCC 2001a; Knutson, Tuleya, and Kurihara 1998; Druyan 1999).

However, there is by no means universal agreement that climate change will visit an increase in violent weather events on PIDCs. Some researchers believe that the purported linkage between increased ocean temperatures and violent weather events is overly simplistic, citing other factors that influence storm development, including atmospheric buoyancy, instabilities in the wind flow, and vertical wind shear (Karl, Nicholls, and Gregory 2001; Holland 1995). Moreover, some climate scientists argue that ocean circulation changes associated with climate change may counter the effects of added warmth (Hileman 1995). In its most recent regional assessment, the IPCC concluded that "[t]here is no consensus regarding the conclusions of studies related to the behavior of tropical cyclones in a warmer world . . . current information is insufficient to assess current trends, and confidence in understanding and models is inadequate to make firm projections" (IPCC 2001a). However, the IPCC did conclude, with "moderate confidence," that the intensity of tropical cyclones is likely to increase by 10–20 percent in the Pacific region when atmospheric levels of carbon dioxide reach double pre-industrial levels (IPCC 2001a).

Potential Impacts of Climate Change on PIDC Freshwater Resources

Sea-Level Rise

As indicated earlier, sea level in PIDCs may rise by an average of 50 centimeters over the next century. Researchers have expressed concern that sea-level rise could result in intrusion of saltwater into the freshwater lenses of coral islands and atolls in the region (Watson, Zinyowera, and Moss 1998). Yet recent research indicates that a rise in sea level of 40–50 centimeters would have virtually no effect on groundwater supplies, or might even raise their volume, because the top of the freshwater lens would rise while its base would remain relatively unaffected (East-West Center 2001, Falkland 1999a). A small rise in sea levels might also be salutary if it raises freshwater lenses to more permeable layers on some islands (Falkland 1999a).

However, this assumes that the width of small islands is not reduced by inundation or erosion in the future. If these phenomena occur as a consequence of climate change, which as indicated earlier is anticipated, groundwater lenses would shrink beneath larger islands and “virtually disappear” under smaller islands (Roy and Connell 1991). For example, a recent study of the impacts of climate-induced sea-level rise on the Bonriki freshwater lens in Tarawa, Kiribati, concluded that the likely reduction of the width of the island by inundation could reduce the thickness of the freshwater lens by 29 percent (East-West Center 2001). The study also concluded that a concomitant rise of sea levels and reduction of rainfall could seriously reduce the volume of freshwater lenses. The study found that a 50-centimeter rise in sea-level in conjunction with a 25 percent reduction in rainfall could reduce the Bonriki freshwater lens by 65 percent, though the study emphasized that most of this impact was attributable to reductions in precipitation (Falkland 1999a).

Moreover, there is the danger that rising sea levels will result in water tables climbing close to or above the land surface, potentially resulting in full evapotranspiration of the resource (Burns 2000). This could ultimately result in groundwater becoming no longer potable on many islands, making human habitation impossible (Roy and Connell 1991). Also, the intrusion of saltwater into freshwater lenses could also result in severe reductions in several subsistence crops in PIDCs, including taro (Wilkinson and Buddemeier 1994; Watson, Zinyowera, and Moss 1998), breadfruit, coconuts (Lobban and Scheffer 1997), and sugarcane (Nunn 1997) as well as lowland forests (SPREP 1999).

Precipitation Changes

As indicated earlier, climate change will likely visit changes in precipitation patterns on many PIDCs, with substantial increases in rainfall in some parts of the region and declines in others. Increased rainfall in the central and eastern tropical Pacific will likely result in a substantial increase in flooding, resulting in the intrusion of seawater through the aquifer recharge zones of islands, substantially reducing potable water supplies, and threatening crops grown in coastal regions (UNEP 1998). If increases in precipitation occur as shorter, but more intense events, recharge of freshwater lenses could drop as water runs off into the sea (SPREP 1999).

As discussed above, climate change could result in an increased incidence of ENSO events, which in the past have been associated with massive decreases in rainfall in the western portion of the Pacific. This could substantially reduce freshwater supplies in nations such as Micronesia and the Marshall Islands, where rainwater is the primary source of supply (SPREP 1999). Decreased rainfall could also diminish the volume of groundwater supplies and contribute to drought conditions in PIDCs, which in the past have been associated with devastating reductions in production of major agriculture export commodities such as sugar cane in Fiji, squash in Tonga (Tutangata 1996), and copra and giant taro in Kiribati (East-West Center 2001). Additionally, serious outbreaks of cholera in PIDCs have been associated with inadequate water supplies during ENSO events (Lobban and Schefter 1997).

Other Impacts

Freshwater resources may be further imperiled if the incidence and/or intensity of storms increase in the Pacific region as a consequence of climate change. Storms can generate waves that result in seawater inundation of groundwater resources, though they can also bring heavy rains that recharge these resources (Falkland 1999a).

Higher temperatures may result in an increase in potential evaporation (atmospheric water demand) rates in tropical regions (Watson, Zinyowera, and Moss 1998). This may accelerate the drying out of soil and vegetation, increasing water demand. Additionally, streamflow on some PIDCs could be affected by the cumulative effects of increased evaporation from watersheds (SPREP 1999).

Recommendations and Conclusions

The impacts described in this chapter are predicated on the assumption that greenhouse gas emissions will reach double pre-industrial levels or higher by the end of this century. Given the rather disheartening record of the parties to the United Nations Framework Convention on Climate Change (UNFCCC) in reducing greenhouse gas emissions, such levels are probably inevitable, and such projections could even prove conservative (Box 5.1).

Thus, it is incumbent upon PIDCs to focus on adaptation strategies to protect and conserve freshwater resources given the increasing threats to such resources that likely will occur during this century and beyond as a consequence of climate change.

Among the strategies that should be pursued by PIDCs are the following:

- A more comprehensive assessment of current water demand and projections of future demand in PIDCs needs to be conducted.
- A sustained research program to assess available fresh water resources on PIDCs is critical to monitor the performance of these resources under natural stresses, such as drought, and stresses associated with human activities such as surface water diversions and pumping. This should include the use of electronic data logging equipment, including hydrological data processing software, to ensure regular reporting and monitoring of water trends in the region. Such research will help to establish baseline information for water managers seeking to assess the additional threats

that may be posed by climate change. Additional training of local staff and island councils in this context should also be a priority.

- More emphasis needs to be placed on rehabilitation and maintenance of water catchment and distribution systems, including efforts to fortify such infrastructure from the possible impacts of climate change, such as violent storms.
- More attention needs to be focused on the impacts of development projects, including tourism infrastructure, on the vulnerability of coastal freshwater resources.
- More attention needs to be placed on controlling leaks from existing water systems, which as indicated earlier, result in the loss of as much as 70 percent of the freshwater resources in some delivery systems. Leakage control programs in nations such as the Seychelles, Malta, and the Bahamas have substantially reduced water loss (UNEP 1998).

There are a number of regional and international organizations that provide funding for research and adaptation programs in the region, including the World Meteorological

Box 5.1 The UN Framework Convention on Climate Change (UNFCCC)

The 186 parties to the UNFCCC, signed on May 9, 1992 (UNFCCC 1992; 31 I.L.M. 849), pledge themselves to “achieve . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” In the face of continued increases in emissions, the parties adopted the Kyoto Protocol in 1997 (Kyoto Protocol 1997). The Protocol calls on industrialized parties to reduce their greenhouse gas emissions by an average of 5.2 percent below 1990 levels in the commitment period of 2008–12. However, despite the fact that the United States, which is responsible for 25 percent of the world’s greenhouse gas emissions, has announced its opposition to the Protocol, the Protocol is a tepid commitment that can have little impact on climate trends. Parry et al. (1998) concluded that full implementation of the Protocol would reduce warming by 2050 by only one-twentieth of one degree Celsius and result in virtually no change in projected sea-level rise. To stabilize atmospheric emissions of CO₂ at double pre-industrial levels (550 parts per million) by the middle of this century would require reductions twenty times as large as those contemplated under Kyoto. It is very difficult to be sanguine that such a commitment by the global community will be forthcoming in the face of evidence that emissions continue to grow rapidly in both developed and developing nations (Arts 2000, IEA 2001). Overall, the International Energy Agency projects that CO₂ emissions will rise 60 percent between 1997 and 2020, with developing countries accounting for the majority of these emissions by the end of this period.

Organization, the United Nations Environment Programme, the South Pacific Applied Geoscience Commission, the South Pacific Regional Environment Programme (SPREP), and the Pacific Island Climate Change Assistance Program of the United Nations Development Program/SPREP. However, funding for these programs is extremely limited and in some cases is declining (Falkland 1999b). While the UNFCCC calls for funding of programs to assist those nations most vulnerable to the impacts of climate change, the parties have been slow to provide for adaptation assistance in developing nations, limiting themselves largely to funding the preparation of reports required under the agreement (Burton 2000). It can be hoped that more funding for such programs will be forthcoming now that several industrialized parties to the UNFCCC have announced their intention to provide \$410 million annually by 2006 for funding climate change programs in developing nations (International Institute for Sustainable Development 2001). However, even this sum is far from adequate to address the vast array of needs of developing countries that will arise from climate change.

While Chinese mythology portrays heaven as a group of rock islands where immortals live blissfully, the existence of Pacific islanders by the end of this century is likely to be far from idyllic. The world's response to the specter of climate change's impacts on these nations will speak volumes as to our commitment to equity and the lot of some of the world's most vulnerable peoples.

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